STRAIN ENHANCED ELECTRON SPIN POLARIZATION OBSERVED IN PHOTOEMISSION FROM InGaAs*

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Abstract

Electron spin polarization in excess of 70% has been observed in photoemission from a 0.1 μm-thick epitaxial layer of $In_xGa_{1-x}As$ with $x \approx 0.13$ grown on a GaAs substrate. Under these conditions, the epitaxial layer is expected to be highly strained by the 0.9% lattice mismatch, as confirmed by X-ray diffractometer measurements of the lattice parameter. The electron polarization and the quantum efficiency have been measured as a function of the excitation photon energy from 1.25 to 2.0 eV. A significant enhancement of the electron polarization occurs in the vicinity of 1.33 eV where the expected strain-induced level splitting permits optical excitation of a single band transition. Measurements made on a control sample of 1.14 μm thickness, significantly larger than the critical thickness for pseudomorphic strain, show no polarization enhancement. These measurements represent the first observation of strain-enhanced electron spin polarization for photoemitted electrons.

I. INTRODUCTION

Polarized electron photoemission from negative-electron-affinity (NEA) GaAs photocathodes is a standard technique to provide a high intensity polarized electron source for linear accelerators. The degeneracy, of the heavy-hole ($j = 3/2$, $m_j = \pm 3/2$) and light-hole ($j = 3/2$, $m_j = \pm 1/2$) valence bands at the Γ point for III-V compounds has limited the maximum polarization to 50% [1]. Reported here is the observation of a significant enhancement in photoemitted electron spin polarization from a single heterojunction of InGaAs grown epitaxially on a GaAs substrate. The growth conditions created a pseudomorphic strain in the InGaAs epilayer by lattice mismatch between the epilayer and the substrate. The strain removes the valence band degeneracy and allows the selective optical excitation of the heavy-hole to conduction band transition.

II. STRAIN-INDUCED BAND STRUCTURE

Strain-induced changes in crystal band structure have been extensively studied [2]. A suitably thin epitaxial layer of InGaAs grown on a GaAs substrate incorporates a biaxial compressive strain in the plane of the interface. Full strain is realized when the lattice spacing of the epilayer in the plane of the interface matches the lattice spacing of the substrate without appreciable production of dislocations. The strain-dependent energy differences between the heavy-hole and light-hole bands, and the conduction band are given by [3]:

$$\begin{aligned} E^{C,HH} &= E_0 + (a\alpha - b\beta)\epsilon \\ E^{C,LH} &= E_0 + (a\alpha + b\beta)\epsilon \end{aligned} \qquad (1)$$

where E_0 is the direct band gap of fully relaxed InGaAs, a and b are the interband deformation potentials, ϵ is the strain, and α and β are functions of the elastic-stiffness constants C_{ij}:

$$\begin{aligned} \alpha &= 2(C_{11} - C_{12})/C_{11} \\ \beta &= (C_{11} + 2C_{12})/C_{11}. \end{aligned} \qquad (2)$$

For biaxial compression these relations imply an increase in the direct band gap and a splitting of the $P_{3/2}$ multiplet with the heavy-hole band gap smaller than the light-hole band gap. Using the deformation potentials and elastic constants for $In_xGa_{1-x}As$ with $x = 0.13$, one obtains a valence band splitting of 61 meV for a fully strained sample. The corresponding heavy-hole and light-hole to conduction band energies are 1.29 eV and 1.35 eV respectively at 293°K.

III. SAMPLE CHARACTERIZATION

The single heterostructures were grown by molecular beam epitaxy (MBE) at the Electronics Research Laboratory of the University of California at Berkeley. The samples grown were a thin strained InGaAs epilayer (thin sample) and a thick relaxed InGaAs layer (thick sample). The substrate material used was (100) n-type GaAs (Si doped to $5 \times 10^{18}\text{cm}^{-3}$). GaAs buffer layers were grown at 600°C to change the carrier type: a 0.6 μm thick n-type GaAs (Si doped to $6 \times 10^{18}\text{cm}^{-3}$) followed by a 0.2 μm thick p-type GaAs (Be doped to $6 \times 10^{18}\text{cm}^{-3}$). The substrate temperature was then reduced to 550°C for the growth of the InGaAs layer. The thin sample had a 0.1 μm thick p-type $In_xGa_{1-x}As$ layer (Be doped to $2 \times 10^{18}\text{cm}^{-3}$ for the first 600 Å and to $4 \times 10^{18}\text{cm}^{-3}$ for the final 400 Å), and the thick sample a 1.14 μm thick p-type $In_xGa_{1-x}As$ layer (Be doped to $2 \times 10^{18}\text{cm}^{-3}$ for the first 11000 Å and to $4 \times 10^{18}\text{cm}^{-3}$ for the final 400 Å). The indium concentration was nominally $x = 0.13$, and the agreement between

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the indium concentration of the two samples was estimated to be $\delta x = \pm 0.01$. After the MBE growth, the sample was cooled to room temperature, and was exposed to an As_4 beam to deposit an arsenic protection layer.

In order to estimate the crystal strain in the InGaAs layer, the samples were analyzed with a double-crystal X-ray diffractometer in the Department of Materials Science and Engineering at the University of Wisconsin. Fig. 1 shows the X-ray rocking curves around the (004) reflection using the CuK_α line. These curves measure the lattice spacing along the growth direction of the epilayers. Since the 1.14 μm-thickness sample is sufficiently thick to be fully relaxed [4], the observed lattice spacing of this sample was used to determine the In concentration giving $x = 0.123$. As a result of the biaxial strain in the heterostructure interface, the InGaAs peak of the 0.10 μm-thickness sample shifts towards a smaller Bragg angle reflecting a lattice expansion along the [001] direction. This implies a biaxial strain for the 0.10 μm-thick sample of $\epsilon = \epsilon^{\parallel} = -0.00859$. Given the uncertainty of the indium concentration of the 0.10 μm-thick sample, this strain corresponds to between 80% and 100% of the fully allowed strain.

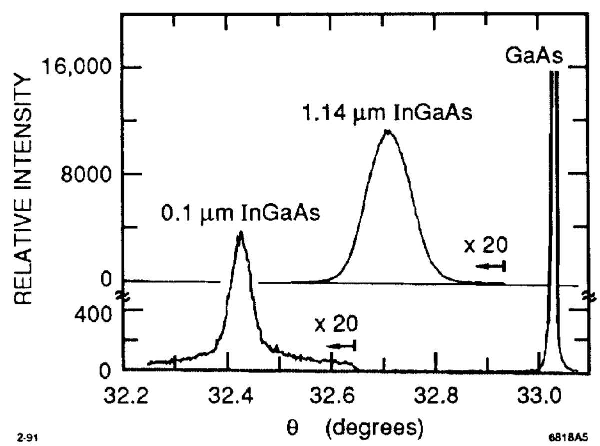

Figure 1. X-ray rocking curves for the (004) reflection from the $In_xGa_{1-x}As/GaAs$ heterostructures.

IV. Experimental Procedures and Results

The electron spin-polarization was measured by Mott scattering at 65 keV. The electron gun and Mott scattering apparatus have been described elsewhere [5]. A nitrogen-laser pumped dye laser, using various dyes to obtain the desired wavelength range, was used as the photoexcitation source. The cathode was activated to obtain an NEA surface using cesium and nitrogen-trifluoride. Prior to activation, the cathode was heat-treated for 1–2 hours at 400–425°C. The arsenic cap layer was removed during the first heat-treatment.

A 2.2 mW HeNe laser was used to measure the absolute quantum efficiency at a photon wavelength of 632.8 nm. A tungsten-halogen lamp and a monochromator, whose output was monitored by a photodiode, were used to measure the relative quantum efficiency as a function of photon energy, and these measurements were then normalized to the HeNe laser measurement at 632.8 nm.

Figure 2 shows the cathode quantum efficiency as a function of excitation photon energy for the two samples. The band gap energies of GaAs and relaxed InGaAs are also indicated. Photoemission was observed down to 1.21 eV indicating that an NEA surface was successfully achieved.

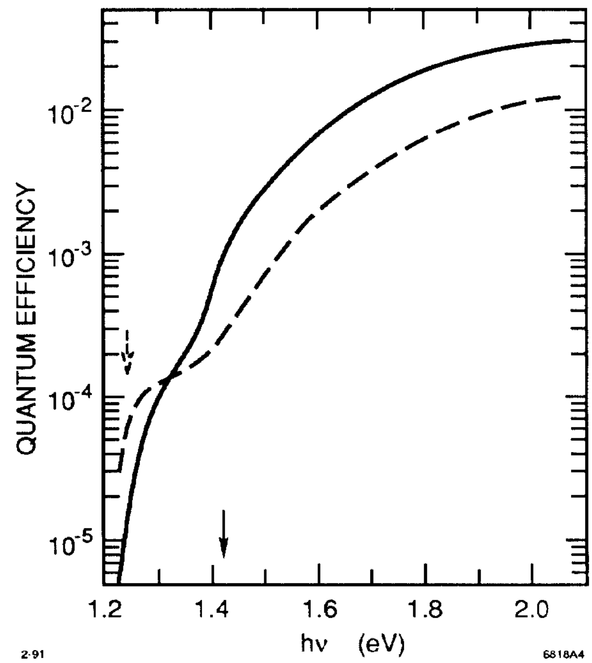

Figure 2. Cathode quantum efficiency as a function of excitation photon energy. The solid curve is for the 0.1 μm-thick sample, and the dashed curve is for the 1.14 μm-thick sample. The band gap energies of GaAs (solid arrow) and relaxed InGaAs (dashed arrow) are indicated.

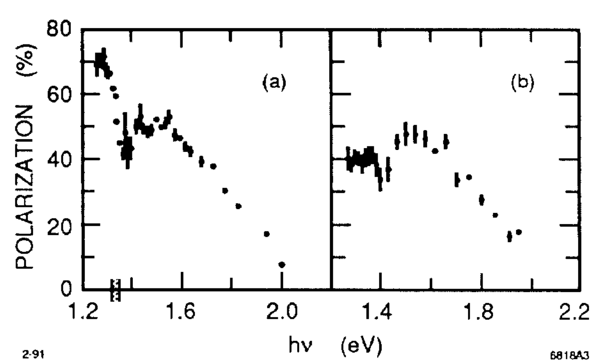

Figure 3. Electron spin-polarization as a function of excitation photon energy for the 0.1 μm-thick sample (a) and for the 1.14 μm-thick sample (b). The shaded region in Fig. 3a shows the expected light hole to conduction band energy difference compatible with the indium concentration uncertainty and the thin sample X-ray analysis.

Figure 3(a) and (b) show the measured electron spin polarization as a function of excitation photon energy for the 0.1 μm-thick sample and the 1.14 μm-thick sample, respectively. The experimental uncertainty shown in the figure includes the statistical error only. In the energy region smaller than 1.34 eV, the spin polarizations of the two samples show a significant difference. The polarization of the 0.10 μm-thickness sample is observed to increase sharply below about 1.34 eV, reaching 71% at about 1.26 eV. The sharp enhancement at about 1.34 eV corresponds to the expected gap energy between the light-hole band and the conduction band for an indium concentration between 0.121 and 0.133, values consistent with the uncertainty in the indium concentration and the thin sample X-ray analysis. By contrast, the polarization of the 1.14 μm-thick sample remains at 40% and shows no such enhancement.

The present polarized source and Mott polarimeter were previously used in a SLAC deep-inelastic scattering experiment where the polarization measured from the Mott polarimeter was crosschecked with the polarization measured from Møller scattering. [6,7] From these measurements the systematic uncertainty of the polarizations reported here is estimated to be $\delta P_{e^-}/P_{e^-} = \pm 0.05$.

V. Summary and Conclusions

The spin polarization has been measured for photoemitted electrons from strained and unstrained InGaAs layers. Polarization in excess of 70% was observed for the 0.1 μm-thick strained InGaAs sample. Polarization for the 1.14 μm-thick unstrained sample was 40% and consistent with the values of bulk III-V compounds. It is concluded that the observed polarization enhancement of the strained sample is due to the strain-induced energy level splitting of the valence band. This measurement is the first observation of strain enhanced electron spin polarization for photoemitted electrons.

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References

[1] T. Maruyama *et al.*, "Enhanced Electron Spin Polarization in Photoemission from Thin GaAs," Appl. Phys. Lett., **55**, 1686–1688, (Oct. 1989).

[2] F. H. Pollak, "Modulation Spectroscopy Under Uniaxial Stress," Surf. Sci., **37**, 863–895, (1973), and references therein.

[3] H. Asai and K. Oe, "Energy Band-gap Shift with Elastic Strain in $Ga_xIn_{1-x}P$ Epitaxial Layers on (001) GaAs Substrates," J. Appl. Phys., **54**, 2052–2056, (Apr. 1983), and H. Kato *et al.*, "Photoluminescence Study of $Ga_xAl_{1-x}P$-GaAs Strained-layer Superlattices," J. Appl. Phys., **59**, 588–592, (Jan. 1986).

[4] P. J. Orders and B. F. Usher, "Determination of Critical Layer Thickness in $In_xGa_{1-x}As$/GaAs Heterostructures by X-ray Diffraction," Appl. Phys. Lett., **50**, 980–982, (April 1987).

[5] C. K. Sinclair, E. L. Garwin, R. H. Miller, and C. Y. Prescott, "A High Intensity Polarized Electron Source for the Stanford Linear Accelerator," in "Proceedings of the Argonne Symposium on High Energy Physics with Polarized Beams and Targets," Argonne, IL, 424–431 (Aug. 1976).

[6] C. Y. Prescott *et al.*, "Parity Non-conservation in Inelastic Electron Scattering," Phys. Lett., **77B**, 347–352, (Aug. 1978).

[7] T. Maruyama and C. Y. Prescott, "Calibration of PEGGY Polarization Measurement," SLAC-SLCPOL Note 25, (Mar. 1989).